Swansea University
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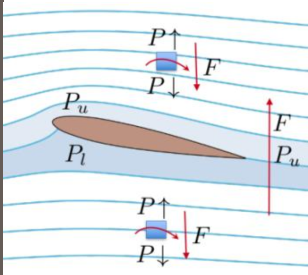
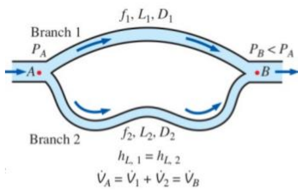
$$\mathrm{Re} = \frac{\rho V L}{\mu}$$

$$\mathrm{St} = \frac{f L}{V}$$





EGF320 - Fluid Flow

Week 3 – External flows

Dr Chennakesava Kapada

Email: c.kadapa@swansea.ac.uk

Website: http://engweb.swan.ac.uk/~c.kadapa/teaching.html

External flows

Chapters 11 and 12

in

Fluid Mechanics (Fifth edition)

by

J. F. Douglas, J. M. Gasiorek, J. A. Swaffield, L. B. Jack

External flows

Fluid flowing over a stationary body

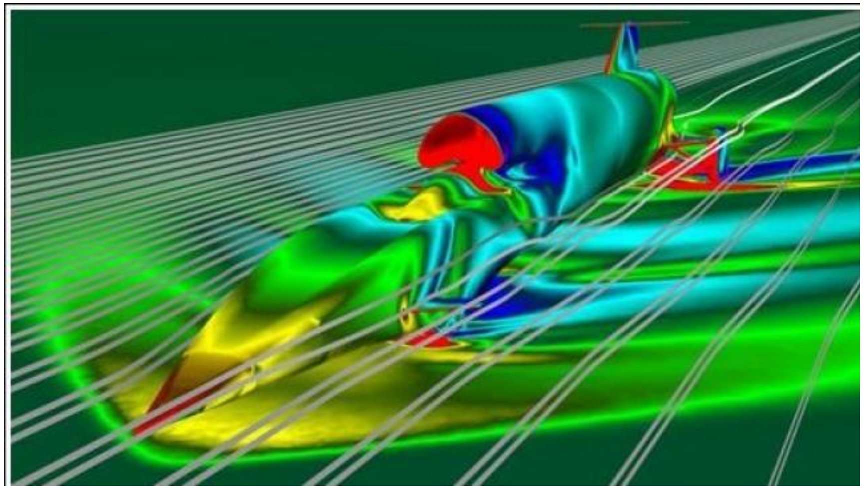
- flow around a building
- flow around bridges
- flow around a wind turbine

A body moving through a fluid

aircraft through air

submarine through water

blood cells



External flows

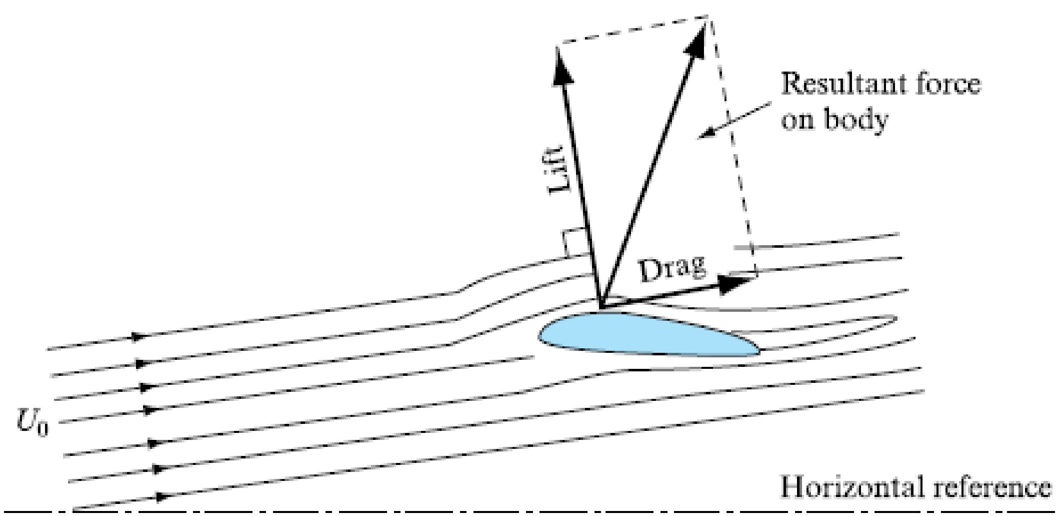
Study of external flows

Involves the estimation of forces acting on the solid bodies.

Total force = Force due to shear + Force due to pressure

Two components:

- **Drag force** – force in line with the direction of motion
- **Lift force** – force perpendicular to the direction of motion



Drag force

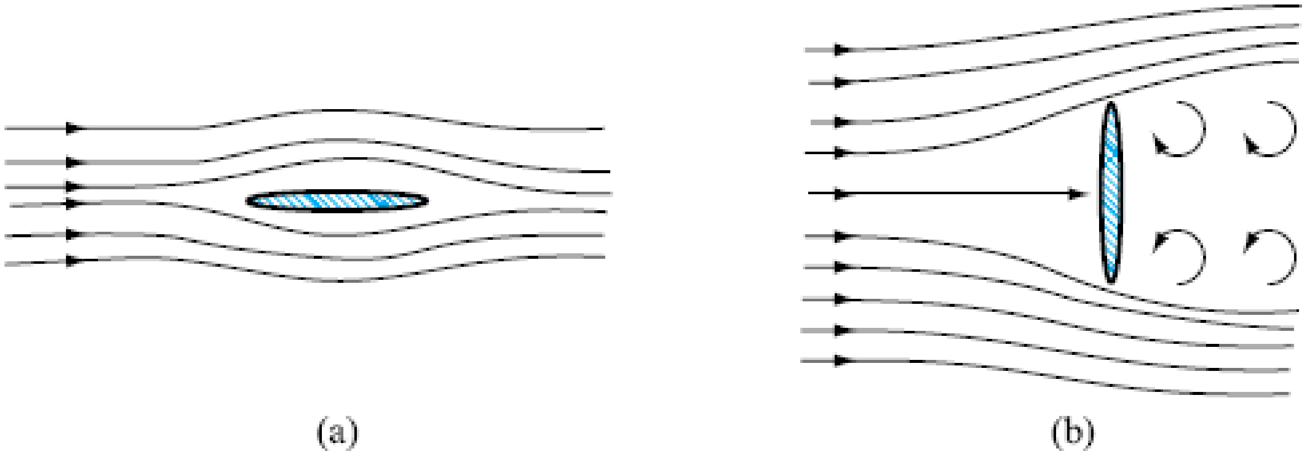
When a body is immersed in a fluid and is in relative motion with respect to it, the ***drag*** is defined as that component of the resultant force acting on the body which is in the direction of the relative motion

Total drag = Pressure drag + Skin friction drag

- Total drag is often called ***profile drag***
- Skin friction drag is the drag force due to shear stresses.

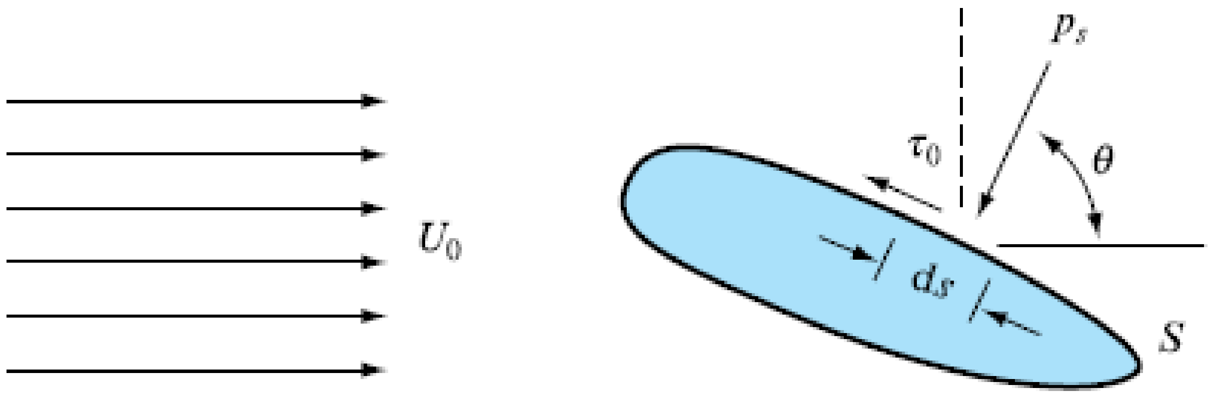
- Skin friction drag is a strong function of viscosity. Hence, increases with increasing viscosity.
- Skin friction drag is dominant for laminar flow while the pressure drag is dominant for turbulent flows

Drag force



- Pressure difference is negligible for the case (a). So, skin friction drag is dominant due to the formation of boundary layer.
- Pressure difference is dominant for the case (b). So, pressure drag is dominant.

Drag and Lift forces



Pressure drag: $D_p = \oint p_s \cos\theta \, ds$

Skin friction drag: $D_f = \oint \tau_0 \sin\theta \, ds$

Total drag: $D = D_f + D_p$

Similarly,

Total lift: $\mathrm{L} = L_f + L_p$

And,

Total force: $\mathrm{F} = \sqrt{L^2 + D^2}$

Drag and Lift coefficients

Drag and lift forces depend on the density of the fluid (ρ), the freestream velocity (U_0), and the size, shape, and orientation of the body.

$$\text{Drag coefficient:} \quad C_D = \frac{D}{\frac{1}{2}\rho U_0^2 A}$$

$$\text{Lift coefficient:} \quad C_L = \frac{L}{\frac{1}{2}\rho U_0^2 A}$$

where, A is frontal area

Note: For thin bodies, such as airfoils, *A is* taken to be the planform area, which is the area seen by a person looking at the body from above in a direction normal to the body.

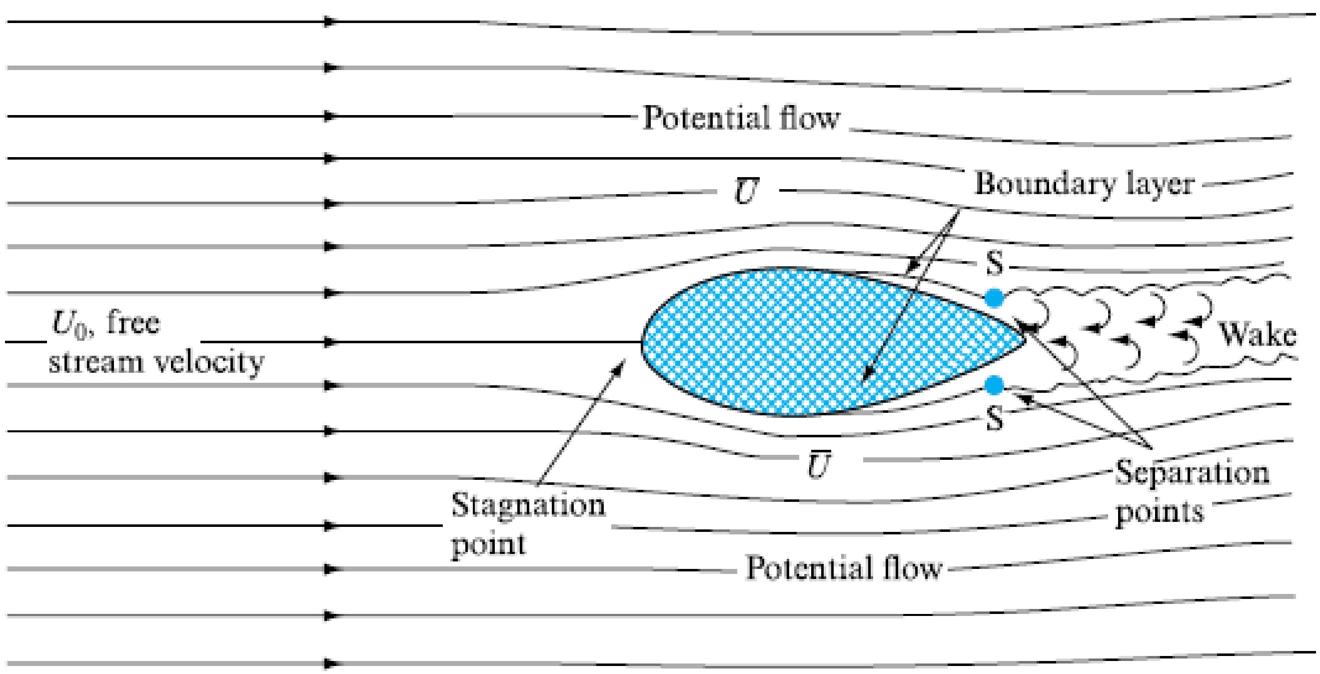
Example 1:

A kite, which may be assumed to be a flat plate of face area 1.2m2 and mass 1.0 kg, soars at an angle to the horizontal. The tension in the string holding the kite is 50N when the wind velocity is 40 km/h horizontally and the angle of the string to the horizontal direction is 35°. The density of air is 1.2 kg/m3.

Calculate the lift and the drag coefficients for the kite in the given position indicating the definitions adopted for these coefficients.

Flow regimes around an immersed body

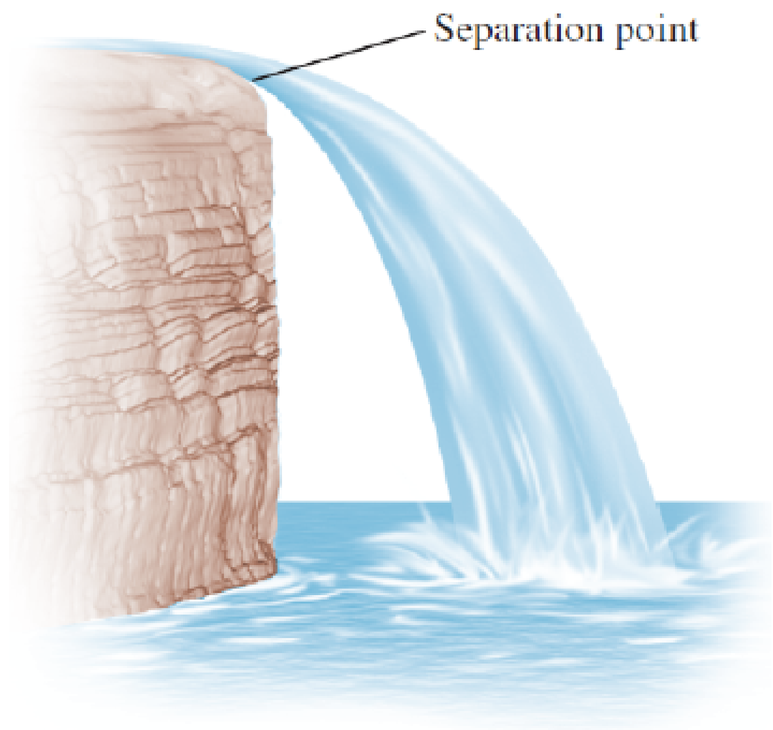
1. Potential flow – velocity field as the gradient of a potential
2. Boundary layer – in the vicinity of the surface
3. Flow separation - detachment of flow from the surface
4. Wake – region downstream of flow separation

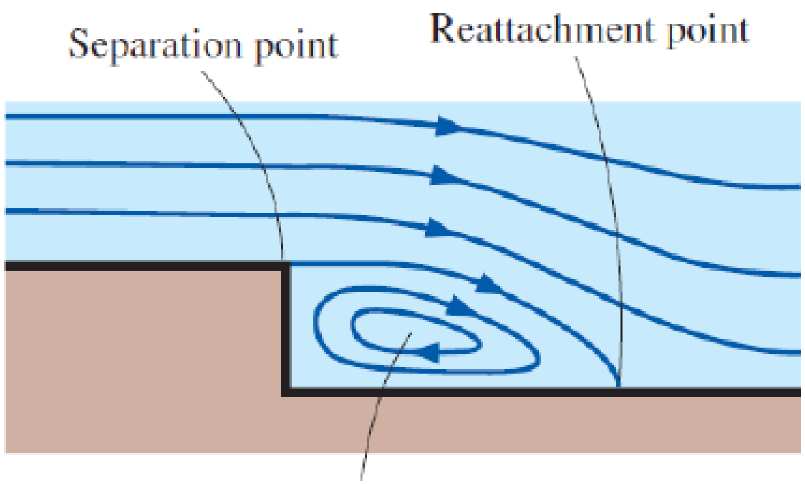


Flow separation and vortices

Flow separation: At sufficiently high velocities, the fluid stream detaches itself from the surface of the body.

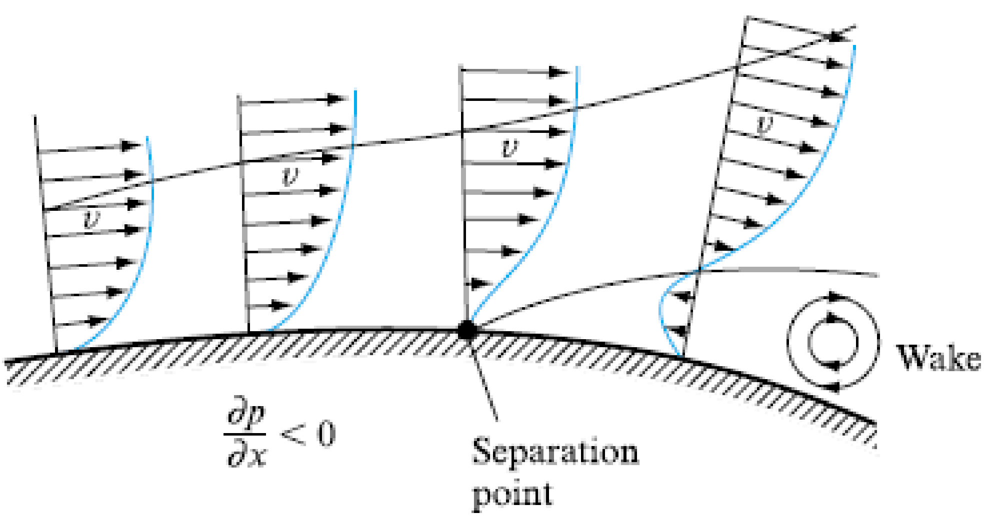
The location of the separation point depends on several factors such as the Reynolds number, the surface roughness, and the level of fluctuations in the free stream, and it is usually difficult to predict exactly where separation will occur.

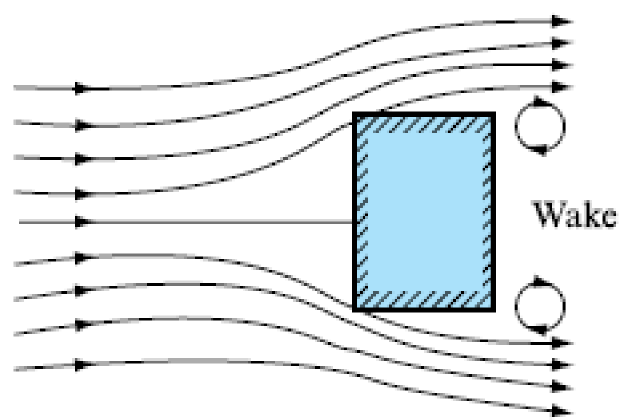




Flow separation and vortices

- When a fluid separates from a body, it forms a separated region between the body and the fluid stream.
- This is a low-pressure region behind the body where recirculating and backflows occur.
- The larger the separated region, the larger the pressure drag.

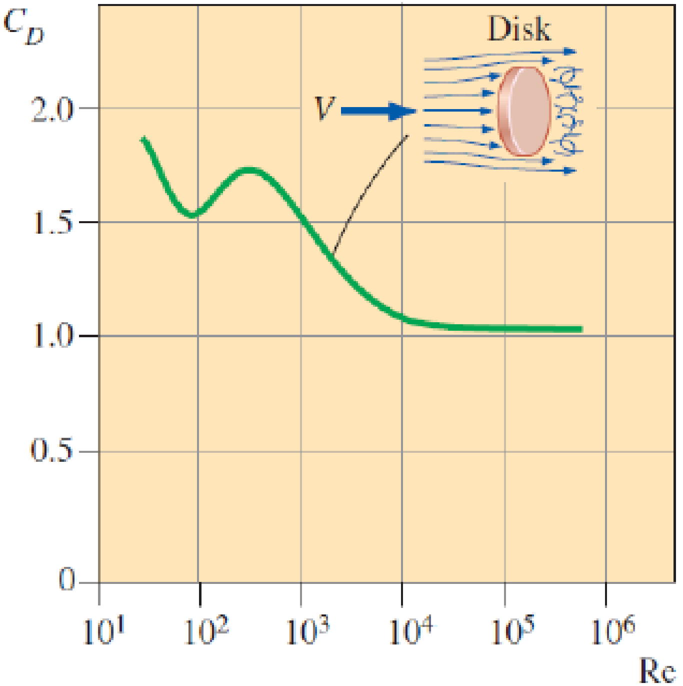




Drag coefficients of some common geometries

The drag behavior of various natural and human-made bodies is characterized by their drag coefficients measured under typical operating conditions.

Usually the *total* (friction+pressure) drag coefficient is reported.



The drag coefficient exhibits different behavior in the low (creeping), moderate (laminar), and high (turbulent) regions of the Reynolds number.

The inertia effects are negligible in low Reynolds number flows (Re < 1), called *creeping flows*, and the fluid wraps around the body smoothly.

$$C_D = \frac{24}{\text{Re}} \qquad (\text{Re} \lesssim 1)$$

Creeping flow, sphere

$$F_D = C_D A \frac{\rho V^2}{2} = \frac{24}{\text{Re}} A \frac{\rho V^2}{2} = \frac{24}{\rho V D/\mu} \frac{\pi D^2}{4} \frac{\rho V^2}{2} = 3\pi\mu V D$$

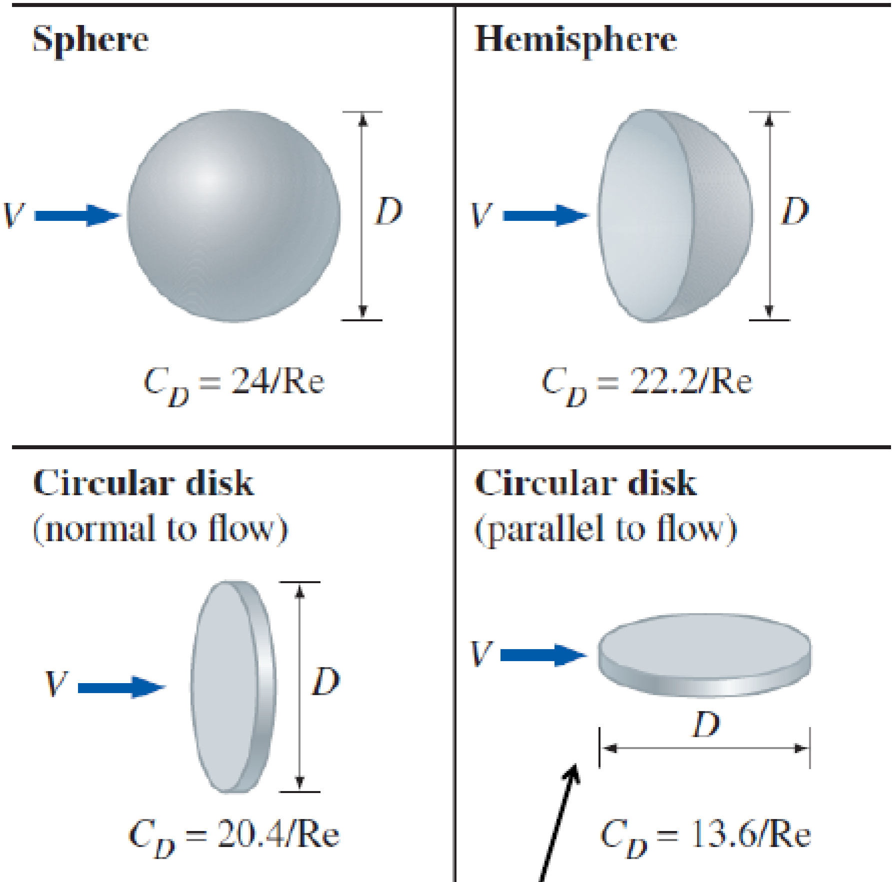
Stokes law

The drag coefficient for many (but not all) geometries remains essentially constant at Reynolds numbers above about 10^4.

Stokes law is often applicable to dust particles in the air and suspended solid particles in water.

Drag coefficients of some common geometries

Creeping flow



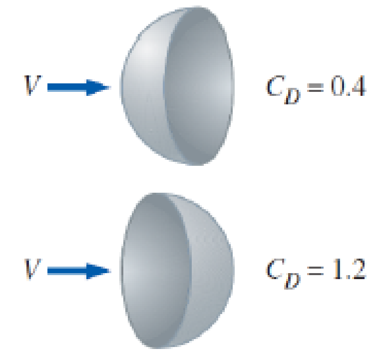
Drag coefficients C_D for creeping flow at low Reynolds number ($\mathrm{Re} \leq 1$ where $\mathrm{Re} = VD/\nu$ and $A = \pi D^2/4$).

Planform area is taken

Some observations

The *orientation* of the body relative to the direction of flow has a major influence on the drag coefficient.

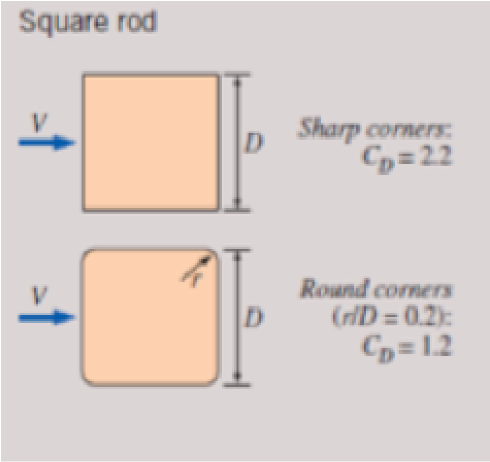
A hemisphere at two different orientations for $Re > 10^4$



For blunt bodies with sharp corners, such as flow over a rectangular block or a flat plate normal to flow, separation occurs at the edges of the front and back surfaces, with no significant change in the character of flow.

Therefore, the drag coefficient of such bodies is nearly independent of the Reynolds number.

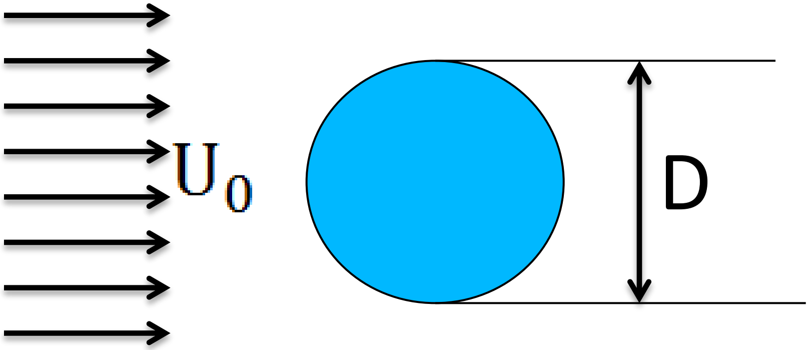
Rounding the edges can significantly reduce drag



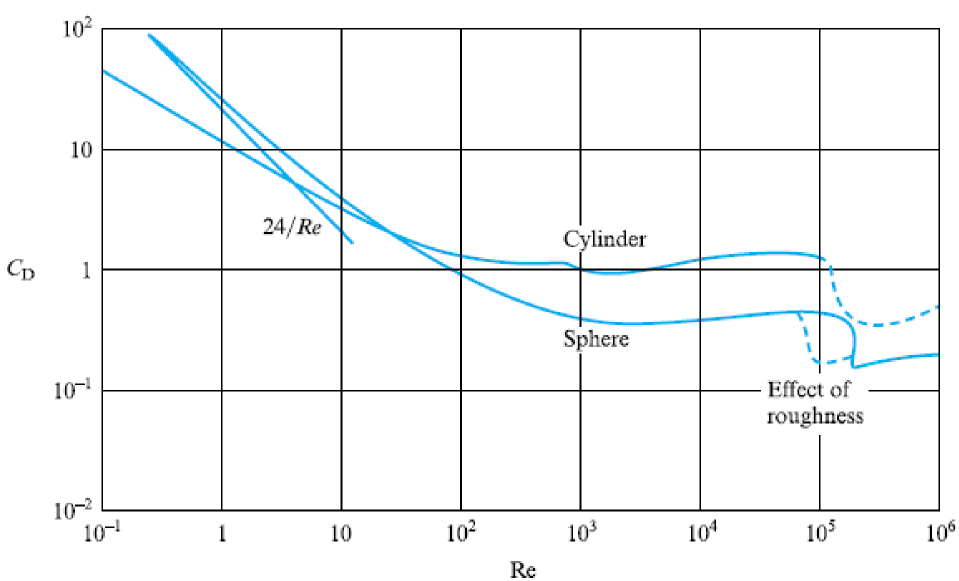
Flow past some common shapes

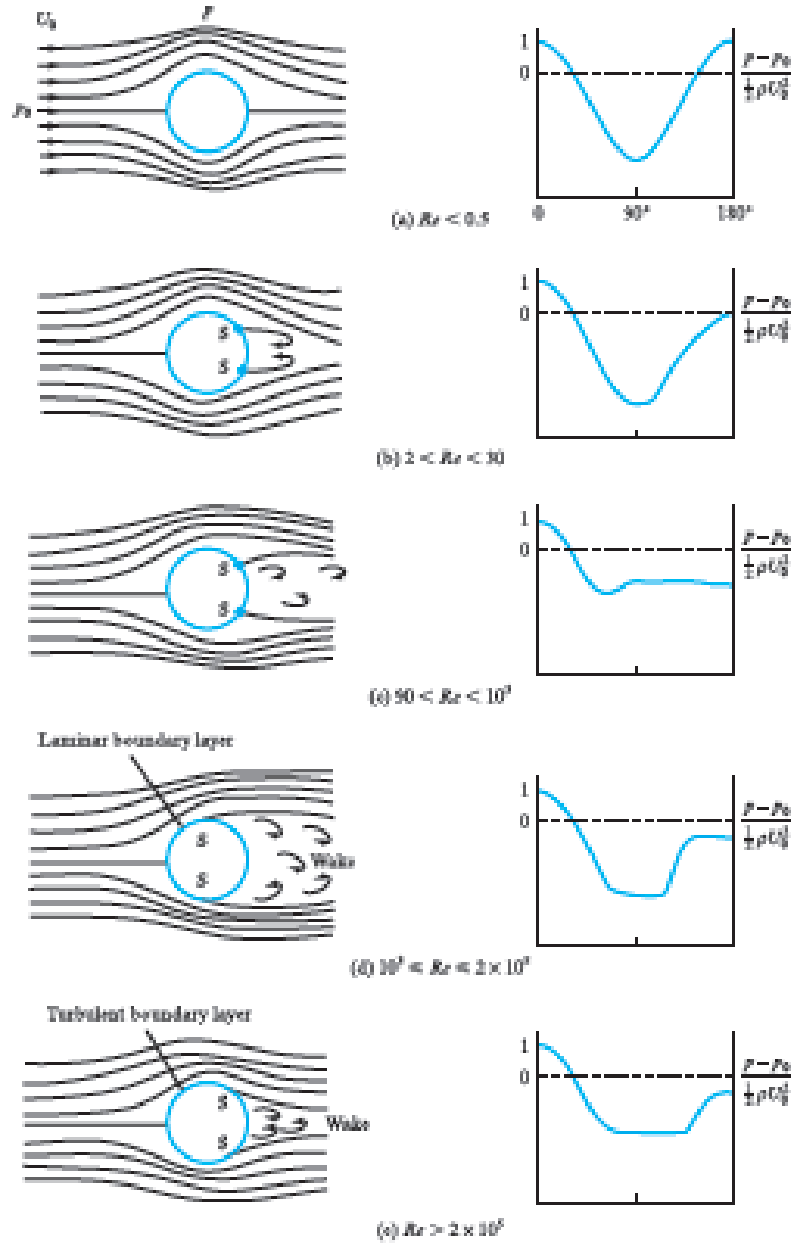
- Flow past a cylinder
  - Cables, wires, tubes
- Flow past a sphere
  - Particulate flows
  - Golf balls
- Flow past an aerofoil
  - Wings, turbine blades

Flow past a cylinder

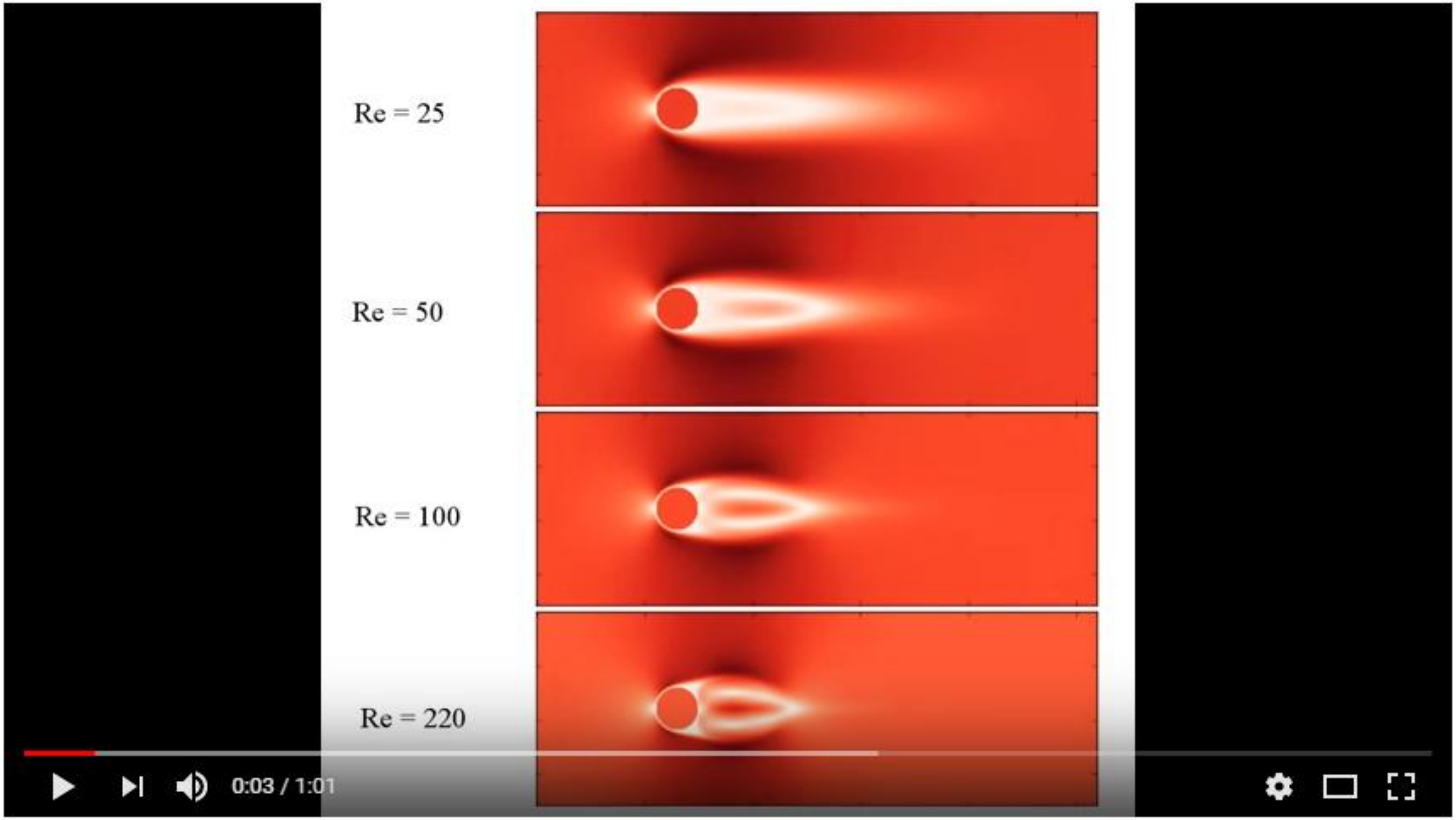


Reynolds number: $\mathrm{Re} = \dfrac{\rho U_o D}{\mu}$



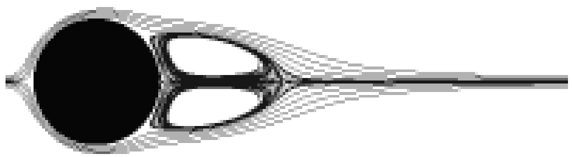


Flow past a cylinder



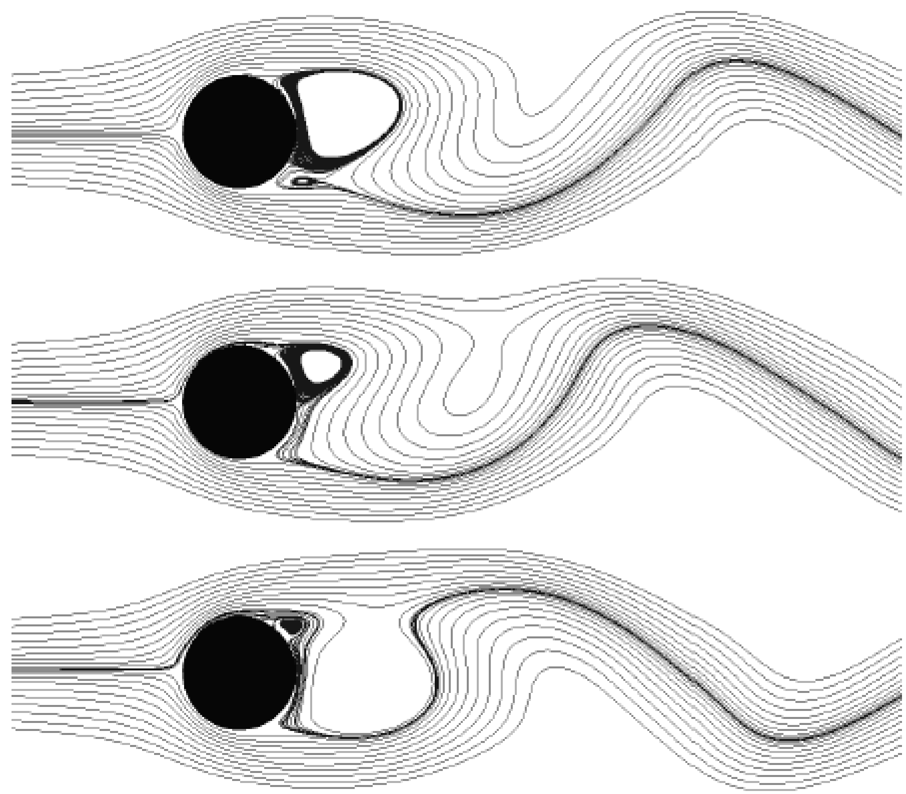
Flow past a cylinder

Re=20



Re=40

Re=100



Flow past a cylinder

- Vortices start developing in a periodic manner for Re>40.
- Famously known as ***von Kármán vortex street.***
- The frequency of vortex shedding varies with Re.

For 250 < Re < 2x10^5,

$$\text{Strouhal number}, St = \frac{fd}{U_0} = 0.198\left(1 - \frac{19.7}{Re}\right)$$

Because of the periodic vortex shedding, the cylinder may be subjected to a forced vibration.
The familiar ‘singing’ of telephone wires is due to this phenomenon.

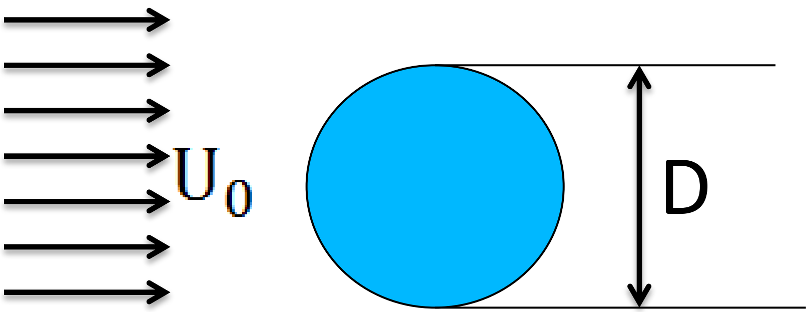
Example 2:

Electrical transmission towers are stationed at 500m intervals and a conducting cable 2cm in diameter is strung between them. If an 80 km/h wind is blowing transversely across the wires, calculate the total force each tower carrying 20 such cables is subjected to.

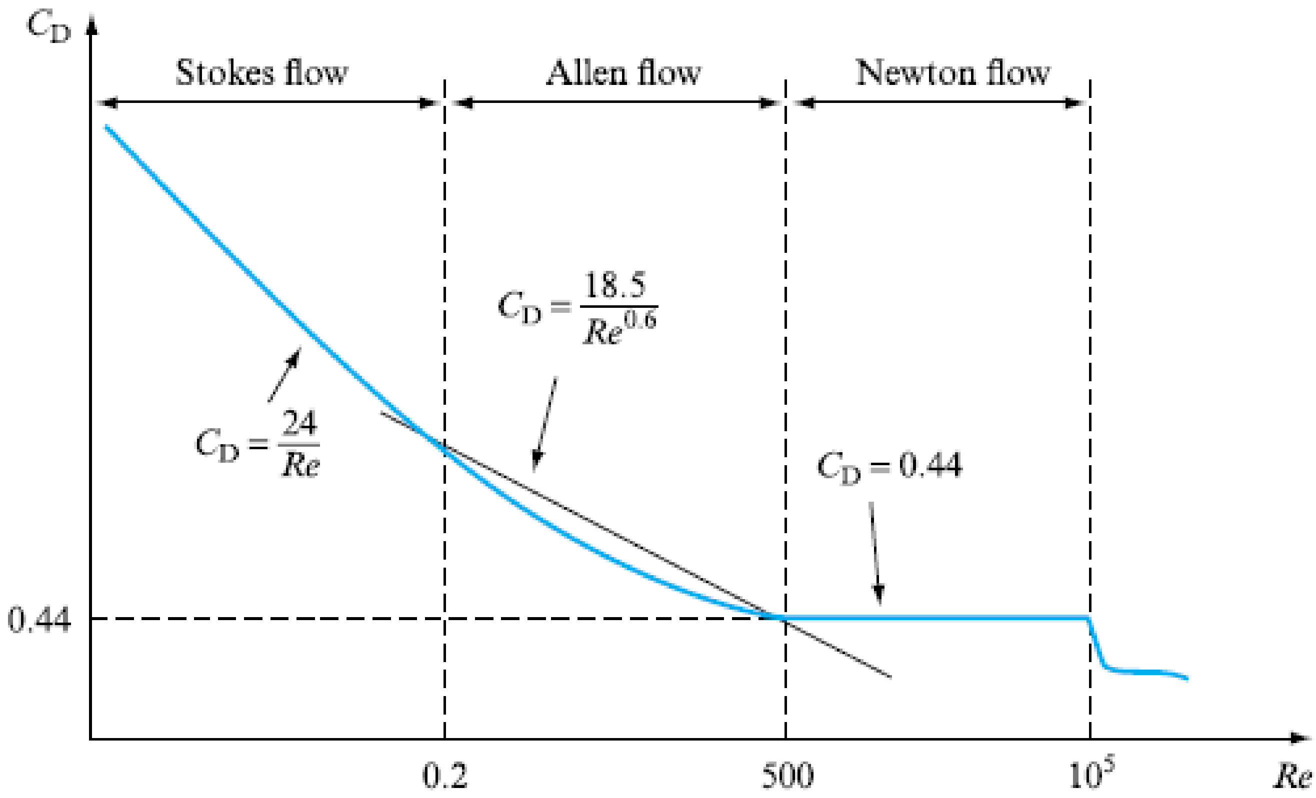
Assume there is no interference between the wires and take air density as 1.2 kg/m3 and viscosity 1.7x10e-5 Ns/m2.

Also establish whether the wires are likely to be subjected to self-induced vibrations and if so what the frequency would be.

Flow past a sphere



Reynolds number: $\mathrm{Re} = \dfrac{\rho U_o D}{\mu}$



Flow past a sphere

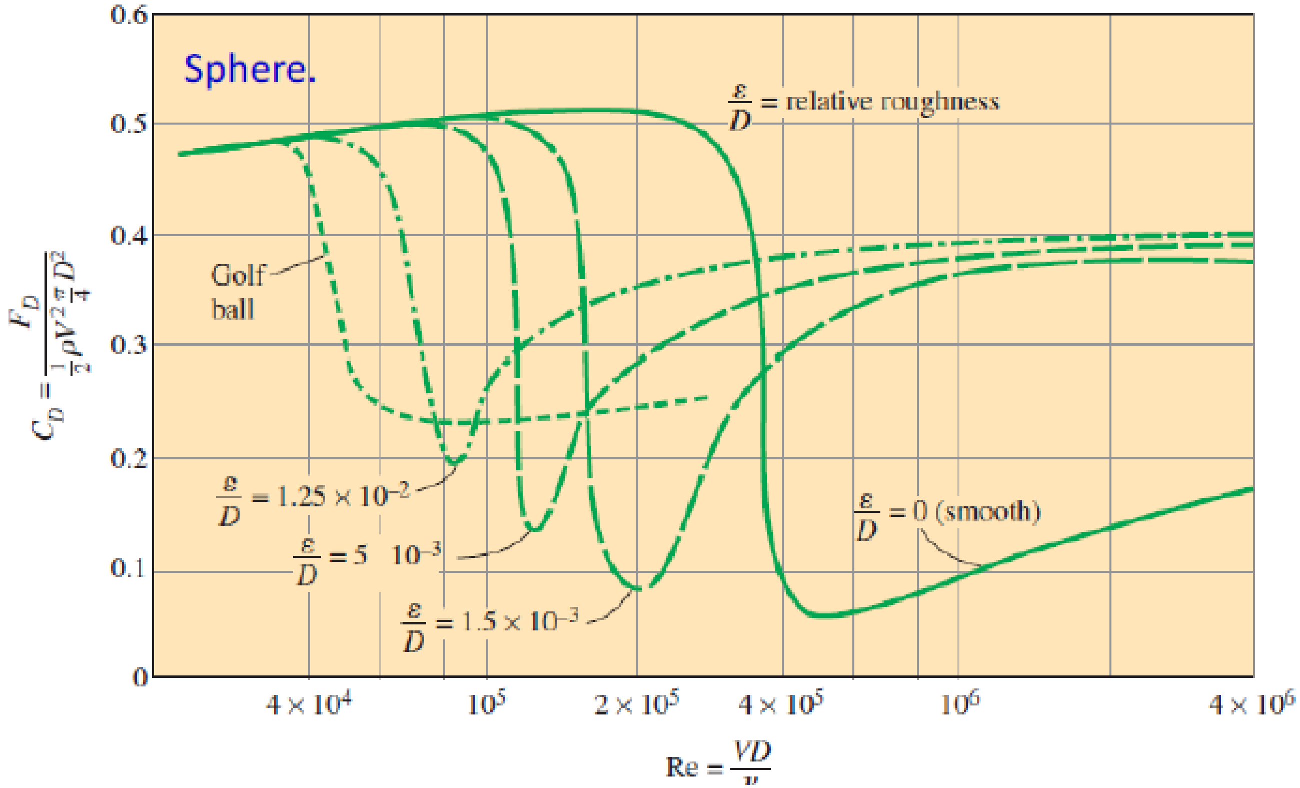
- For Re<1, we have creeping flow, and the drag coefficient decreases with increasing Reynolds number. For a sphere, it is C_D=24/Re. There is no flow separation in this regime.
- At about Re=10, separation starts occurring on the rear of the body with vortex shedding starting at about Re=90. The region of separation increases with increasing Reynolds number up to about Re=10^3. At this point, the drag is mostly (about 95 percent) due to pressure drag. The drag coefficient continues to decrease with increasing Reynolds number in this range of $10<Re<10^3$.
- In the moderate range of $10^3<Re<10^5$, the drag coefficient remains relatively constant. This behavior is characteristic of bluff bodies. The flow in the boundary layer is laminar in this range, but the flow in the separated region past the cylinder or sphere is highly turbulent with a wide turbulent wake.
- There is a sudden drop in the drag coefficient somewhere in the range of $10^5<Re<10^6$ (usually, at about 2×10^5). This large reduction in C_D is due to the flow in the boundary layer becoming *turbulent*, which moves the separation point further on the rear of the body, reducing the size of the wake and thus the magnitude of the pressure drag. This is in contrast to streamlined bodies, which experience an increase in the drag coefficient (mostly due to friction drag) when the boundary layer becomes turbulent.
- There is a "transitional" regime for $2\times10^5<Re<2\times10^6$, in which C_D dips to a minimum value and then slowly rises to its final turbulent value.

Surface roughness

Surface roughness, in general, increases the drag coefficient in turbulent flow.

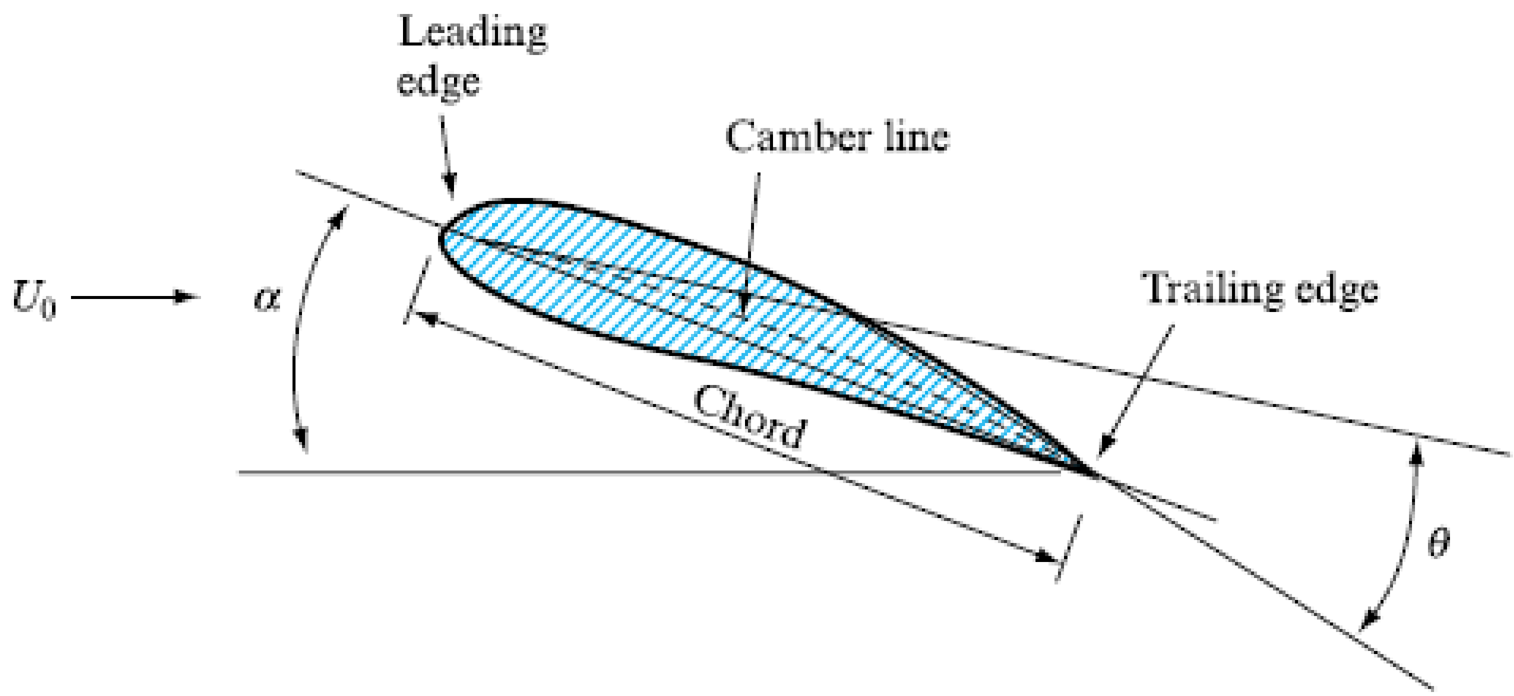
This is especially the case for streamlined bodies.

For blunt bodies such as a circular cylinder or sphere, however, an increase in the surface roughness may *increase* or *decrease* the drag coefficient depending on Reynolds number.



golf balls are intentionally roughened to induce turbulence at a lower Reynolds number

Flow past aerofoils



Flow past aerofoils

Leading edge	the front, or upstream, edge, facing the direction of flow;
Trailing edge	the rear, or downstream, edge;
Chord line	a straight line joining the centres of curvature of the leading and trailing edges;
Chord, c	the length of chord line between the leading and trailing edges;
Camber line	the centreline of the aerofoil section;
Camber, δ	the maximum distance between the camber line and the chord line;
Percentage camber	$= 100\delta/c$ per cent is a measure of aerofoil curvature;
Span, b	the length of the aerofoil in the direction perpendicular to the cross-section;
Plan area, A	the area of the projection of the aerofoil on the plane containing the chord line. If the aerofoil is of constant cross-section, $A = c \times b$;
Mean chord, $\bar{c}$	$= A/b$;
Aspect ratio, AR	$=$ (Span)/(Mean chord) $= b/c = b^2/A$;
Deviation, θ	angle between the tangent to camber line at trailing edge and the tangent to camber line at leading edge;
Angle of attack (incidence)	the angle between the direction of the relative motion and the chord line;
Pressure coefficient, C_p	$= (p - p_0)/\frac{1}{2}\rho U_0$, where p is the local pressure and p_0 is the pressure far upstream of the aerofoil where velocity is V_0.

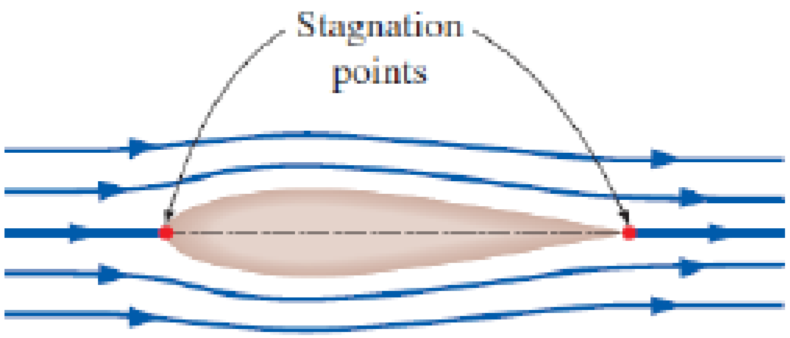
Flow past aerofoils

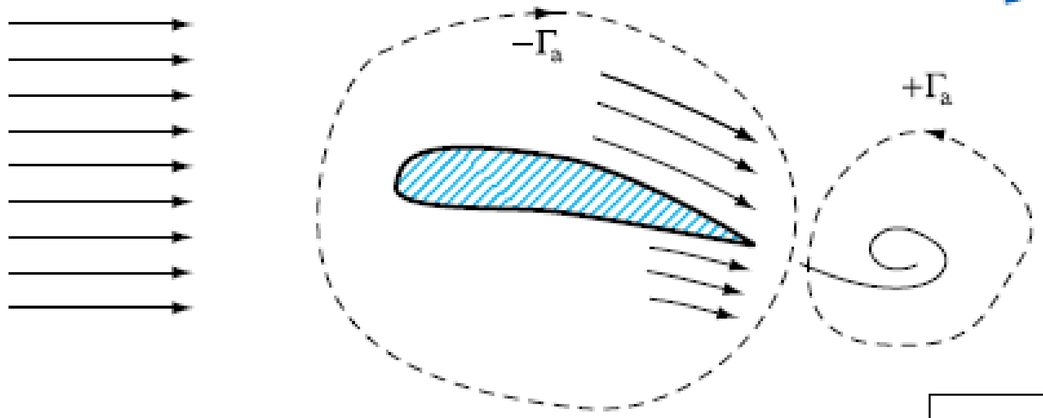
- The primary purpose of aerofoil is to produce lift when placed in a fluid stream.
- The design aerofoils is concerned with maximising the lift and minimising the drag.
- Characterised by lift-to-drag ratio.

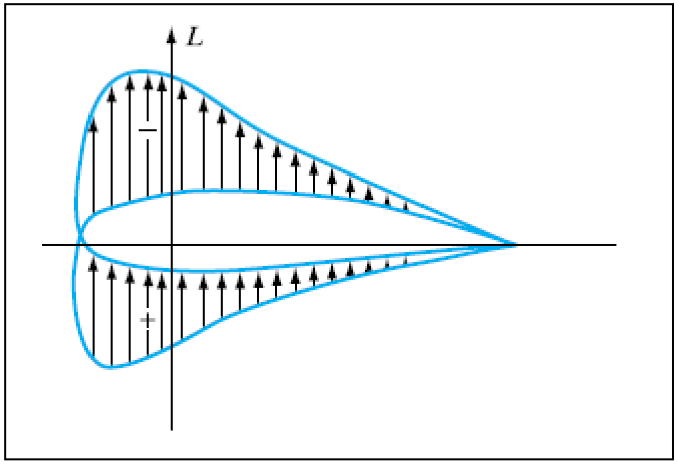
$$\text{Lift to Drag ratio,} \frac{L}{D} = \frac{C_L}{C_D}$$

Flow past aerofoils

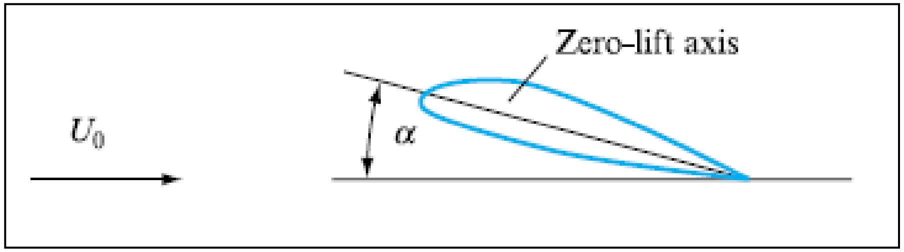
How does aerofoil produce lift?





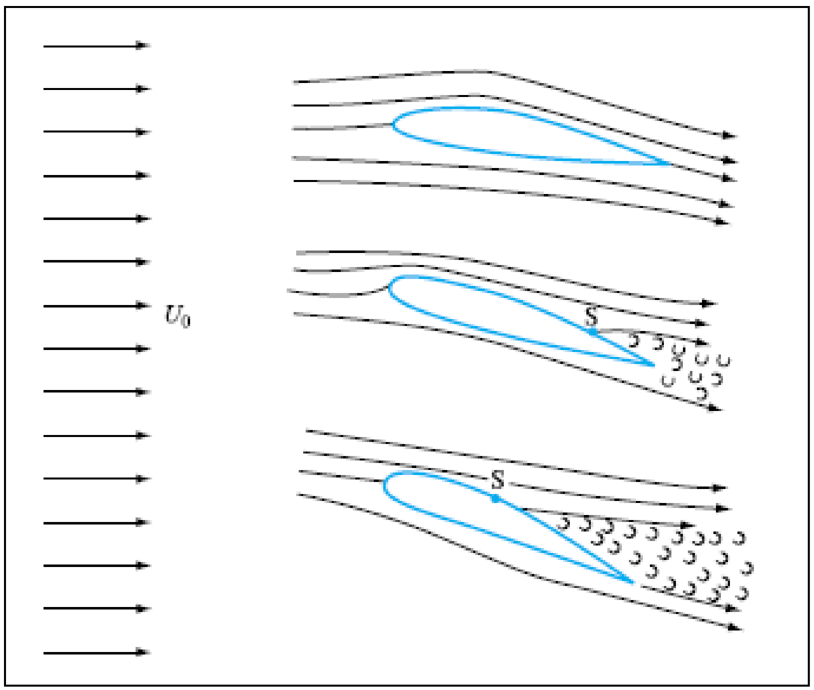


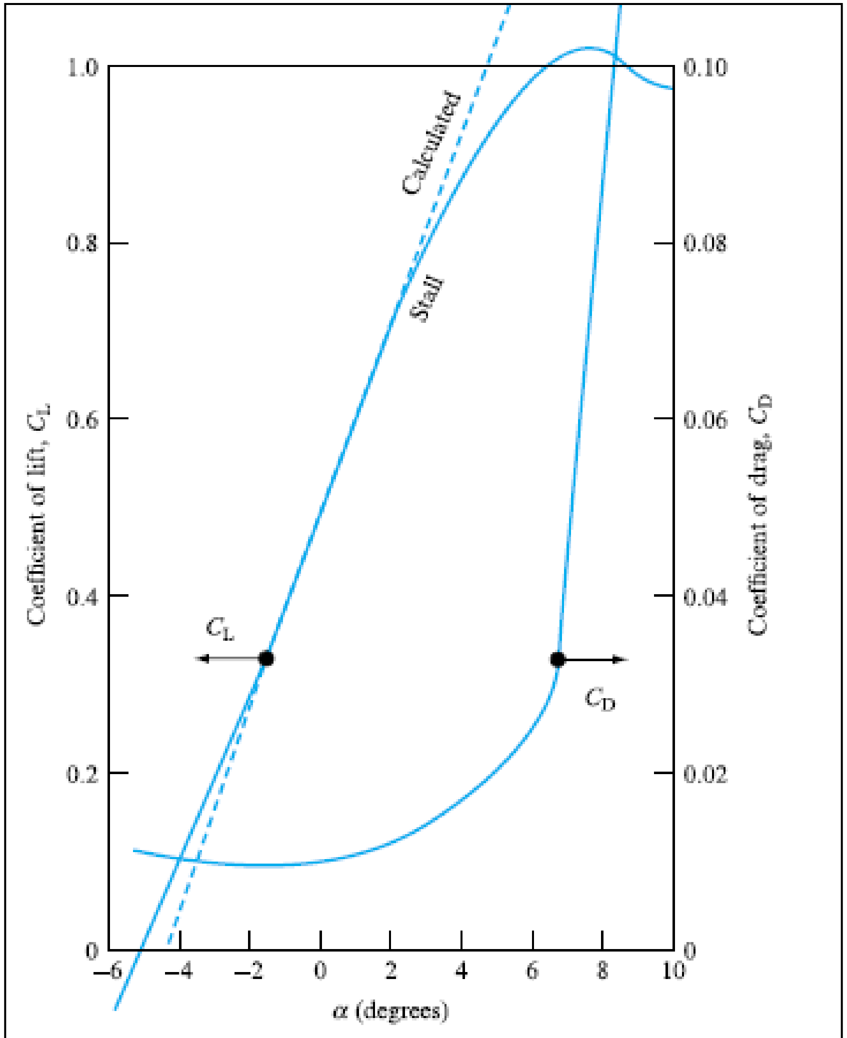
Flow past aerofoils



Using Kutta-Joukowsky's theorem,

$$\text{Coefficient of lift, } C_L = \frac{8\pi a}{A} \sin\alpha$$





Flow past aerofoils

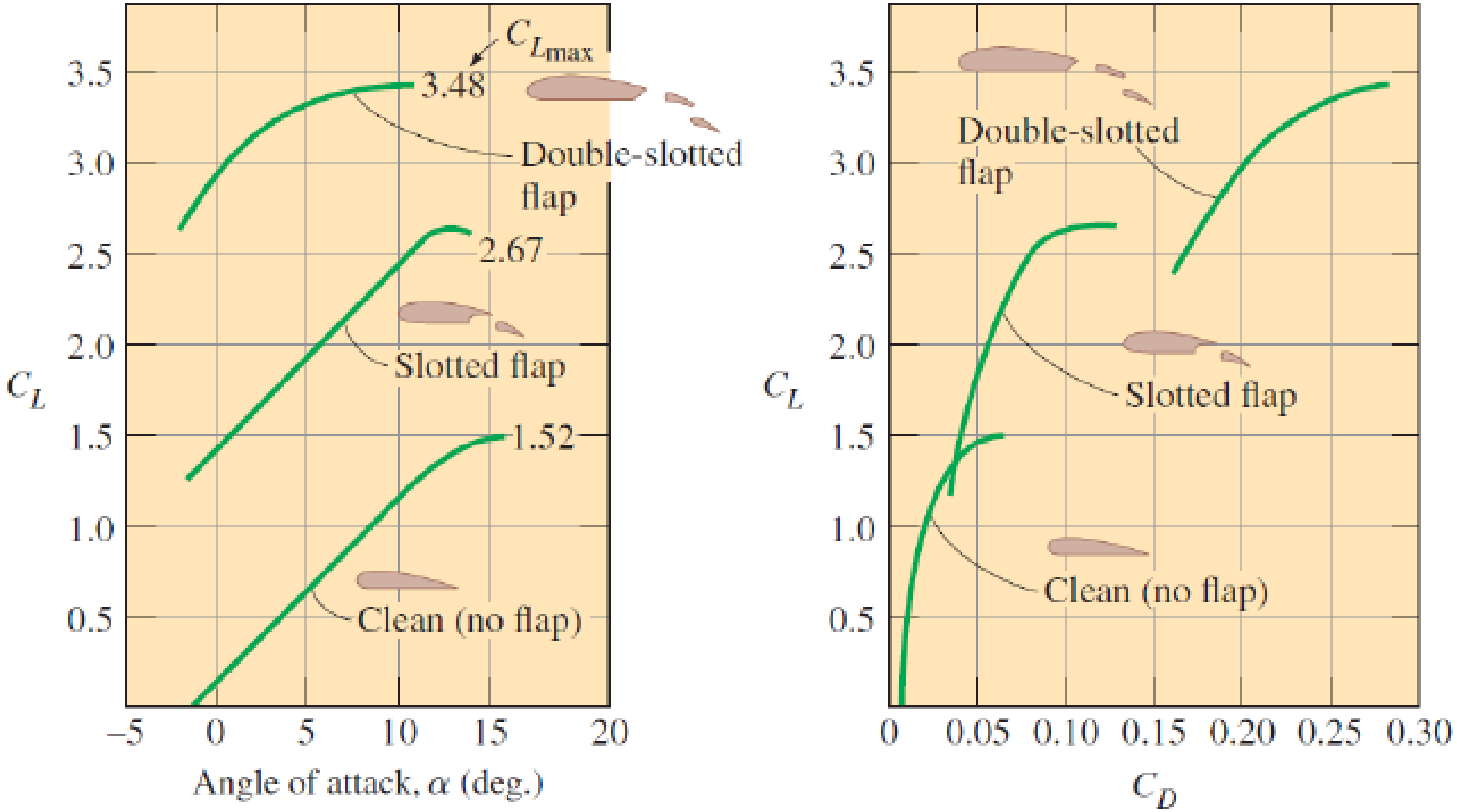
The lift and drag characteristics of an airfoil during takeoff and landing can be changed by changing the shape of the airfoil by the use of movable flaps.

(*a*) Flaps extended (landing)

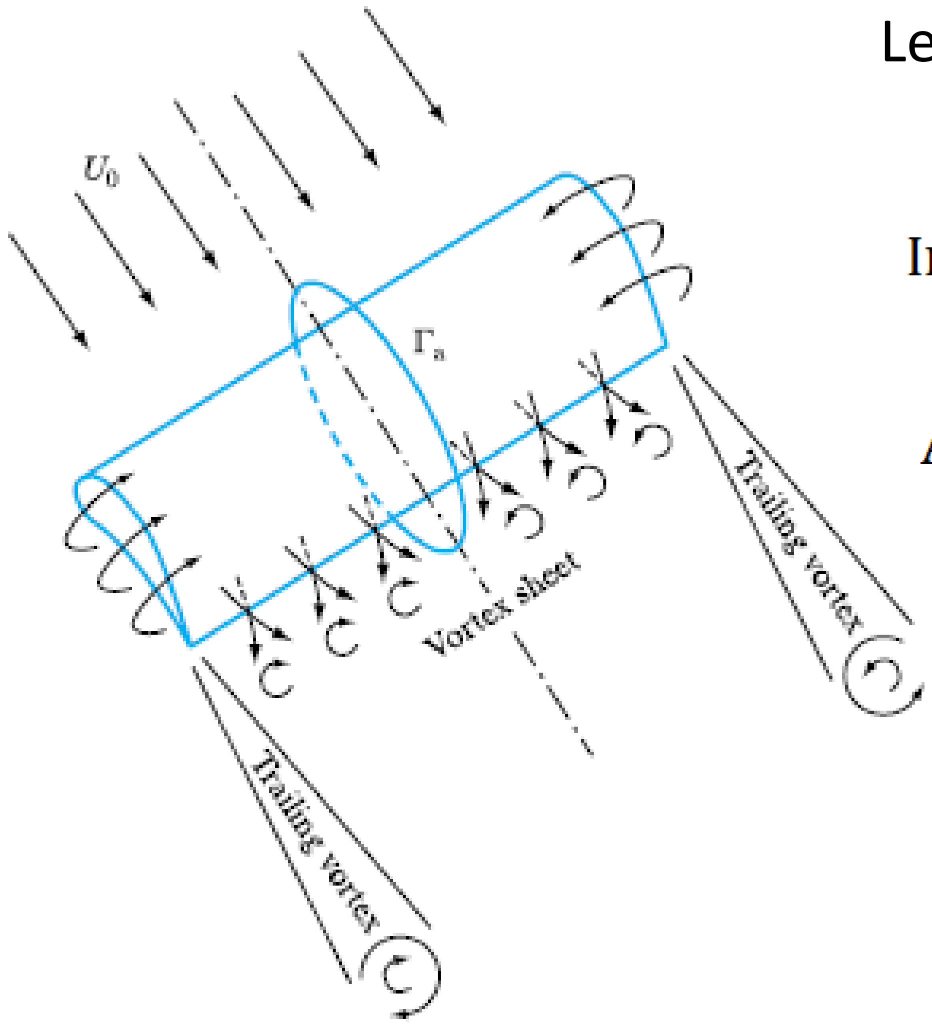
(*b*) Flaps retracted (cruising)

Flow past aerofoils

Effect of flaps on the lift and drag coefficients



Flow past an aerofoil of finite length



Leads to **induced drag**

Induced drag, $C_{D_i} = \dfrac{C_L^2}{\pi\,\lambda}$

Aspect ratio, $\lambda = \dfrac{b}{c}$

Example:
A wing of an aircraft of 10 m span and 2 m mean chord is designed to develop a lift of 45 kN at a speed of 400 km h−1. A 120 scale model of the wing section is tested in a wind tunnel at 500 m/s and ρ = 5.33 kg/m^3. The total drag measured is 400 N.
Assuming that the wind tunnel data refer to a section of infinite span, calculate the total drag for the full-size wing. Assume an elliptical lift distribution and take air density as 1.2 kg/m^3